NEAR-FIELD RADAR SIGNATURE MODELING FOR EW/END-GAME SIMULATIONS

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ABSTRACT

The effectiveness of radar-guided weapons can be compromised by a number of factors, such as target glint, engine modulation, clutter and electronic counter measures (ECM). In fact, many missile intercept failures often were attributed to these factors. Thus, effective weapon systems design must carefully consider these effects in order to avoid serious degradation of the weapon performance. By employing modeling and simulation, effective design can be achieved with relative ease and significant cost-savings.

For missile fuzing/ECM applications, the transmitting and receiving antennas on the missile are generally located in the near-field zone of the scattered field from the target encountered. In consequence, the radar return computation is complicated by the partial target illumination, nonuniform antenna patterns, target material coatings, and engine inlet returns. Existing near-field radar cross section (RCS) computation algorithms are typically based on first-order high frequency methods that do not account for multiple bounce and complex shadow effects. In particular, those algorithms cannot be used to calculate scattering from a cavity, such as an engine inlet or a sensor box. The cavity scattering, material coatings and engine modulation are, however, known to be crucial contributors in fuzing and ECM end-game missile/target encounter simulations. A successful missile/target engagement analysis must thus be conducted with accurate near-field target signature information that includes effects attributable to multi-bounce, material coatings, antenna patterns, *etc.*. This paper discusses techniques and methodologies for solving near-field modeling and simulation problems in missile/target end-game scenarios.

1.0 INTRODUCTION

Radar-guided weapons rely on the electromagnetic energy scattered or radiated by the target for weapon guidance and for proximity fuzing of the warhead. Owing to the rich signal environment in which radar-guided weapons must operate, their effectiveness can be compromised by several factors. The power of clutter energy in the band of the radar frequently far exceeds that of the target signal, which can pose difficulties for maintaining target track. Even when the clutter is properly filtered, glint in the target signal can cause rapidly changing estimates of the target's angular location with respect to the missile, with attendant problems for reliable guidance. Target return also contains amplitude and phase modulation from the rotating engine turbines. This introduces additional Doppler spectra which can confuse the pulse-Doppler (PD) radars frequently used in radar-guided weapons. Finally, jamming signals are often present, with the specific intent of degrading weapon effectiveness. Jammers can overload or confuse the guidance radar or induce a premature fuzing of the warhead. Well-designed missiles have mechanisms to counter at least some of these problems. Ultimately, then, missile intercept failure may be blamed on missile system design that inadequately deals with glint, clutter, jamming, *etc.*

To assess the effectiveness of radar-guided weapon systems, laboratory and live-firing test and evaluation capabilities are required to conduct system performance analyses and engineering investigations for identifying and correcting system design problems. Due to the high cost of flight tests, however, weapon system performance evaluation is primarily relying on digital simulation or missile hardware-in-the-loop (HIL) flight simulation in a complicated RF-threat environment. In a digital or HIL weapon system simulation, the electromagnetic (EM) wavefront (amplitude and phase) perceived by the radar sensors (missile seekers and target detection devices) is most critical to a valid and realistic missile performance simulation. Accurate target-modeling for predicting the wavefront characteristics is essential to a successful digital or HIL simulation.

While missile and radar simulators are not new, relatively little attention has been paid to realistic, high-fidelity, near-field target scattering. This is particularly true for end-game simulations where near-field EM effects of the radar sensors and target are rarely well understood or modeled. Typically, a statistical radar cross-section (RCS) model is used in conjunction with a random process to generate target scattering data [1]. While this approach has the merit of simplicity and low computational burden, it suffers in two ways. First, statistical models are target aspect independent, so particular scenarios involving target aspect cannot be explored. More importantly, these models break down in the intermediate and near-zones (see Fig. 1). So, the effect of target glint and the Doppler spread of the target scattering during the end-game fuzing are not handled well. With the advent of new computers and computational methods, it is now possible to make major upgrades to radar simulations for near and far-field target scattering.

For missile fuzing/ECM applications, the transmitting and receiving antennas on the missile are generally located in the near-field zone of the scattered field from the target encountered. In consequence, the radar return computation is complicated by the partial target illumination, nonuniform antenna patterns, target material coatings, and engine inlet returns. Existing near-field radar cross section (RCS) computation algorithms, such as NcPTD [2], are typically based on first-order high-frequency methods that do not account for multiple bounce and complex shadow effects. In particular, those algorithms cannot be used to calculate scattering from a cavity, such as an engine inlet or a sensor box. The cavity scattering, material coating and engine modulation are, however, known to be crucial contributors in fuzing and ECM end-game missile/target encounter simulations. A successful missile/target engagement analysis must thus be conducted with accurate near-field target signature information that includes effects attributable to multi-bounce, material coatings, antenna patterns, *etc.*. In addition, the Doppler effects, engine modulation, clutter and jamming need to be included in the near-field modeling for missile/target end-game scenarios.

The Naval Air Warfare Center Weapons Division (NAWCWPNS) is the Department of the Navy's prime research, development, test and evaluation (RDT&E) center for weapons system development, acquisition and life-cycle support. To meet the requirements of future weapons system development, test and evaluation, the NAWCWPNS is actively pursuing upgrade and expansion of its current digital modeling, hardware-in-the-loop (HIL) and electronic countermeasures (ECM)/electronic counter-countermeasures (ECCM) system simulation capabilities. To that end, NAWCWPNS is funding and collaborating with two private contractors to conduct independent research efforts in near-field signature modeling. This paper describes the results achieved in one of these efforts, by DEMACO, Inc., in developing an improved digital radar-signature simulation model suitable for radar-guided missile simulation from mid-flight through end-game. A discussion of the digital radar-signature simulator, which uses SBR as the core EM modeling techniques for the near-field modeling, will be given in the following section. Preliminary results obtained in the last six months will be presented to illustrate the progress and accomplishment achieved. Plans for future development will also be discussed. A later paper will describe progress in the other, independent effort conducted by Spectra Research, Inc. and McDonnell Douglas Aerospace.

2.0 TECHNICAL APPROACH

The practical problem addressed by this paper is the simulation of end-game encounters between a radar-guided missile and their targets. In the end-game, the target and missile are in close proximity, and the missile uses its radar to determine the optimal time to fuze the warhead for detonation. Electromagnetic (EM) scattering phenomena play a critical role in the end-game since EM scattering determines the missile radar received signal levels used for warhead detonation. To that end, the R&D effort had the main objective of developing a prototype general-purpose predictor suitable for missile/target end-game scenarios and that includes the effects of the missile antenna pattern, multiple reflections, complex-shape shadowing, and material coatings. An additional objective was the development of suitable techniques for modeling the scattering from the target engine cavity, including effects of modulation (i.e., Doppler spectra) produced by rapid blade rotation.

In order to satisfy these objectives, we chose a high-frequency approximation, shooting and bounce rays (SBR) method, as the core EM computational engine for the near-field modeling development. SBR uses geometrical optics (GO) ray tracing to implement physical optics (PO) [3] and is suitable for near missile/target encounters where the target spans a range of aspect angles with respect to the missile. SBR has the following advantages and features:

a) SBR gracefully handles highly complex and realistic CAD models, with no need for model pre-processors or mesh generators,

b) includes multi-bounce scattering mechanisms,

c) easily handles surfaces coated with layers of materials, and

d) inherently includes PO diffraction effects for both metallic and coated edges.

The SBR method is particularly suitable for electrically large and geometrically complex targets represented by CAD models, as discussed in [3,4], and has been proven to be accurate for both metallic and non-metallic materials. The near-field scattering predictor currently in development and described here, NPATCH, computes the near-field multi-bounce radar scattering from complex, realistic targets illuminated by missile fuzing antennas. Like the XPATCH [3,4] RCS code, NPATCH uses 3-D ray tracing on CAD models composed of triangular facets to implement a PO/SBR scattering solution. It also includes the radiation and receiving patterns of the missile fuzing and tracking antennas. NPATCH has significant capability and accuracy enhancements over its predecessor near-field code, NcPTD. While NcPTD is a standard near-field code widely used throughout the Department of Defense, it suffers from several limitations. NcPTD is a single-bounce physical optics (PO) code for simple geometries defined by plates, cylinders, curved surfaces, cones, etc. It contains no ray tracer for accurate and automated determination of complex shadowing and, thus, cannot handle today's class of realistic 3-D CAD target models. Without a ray tracer, NcPTD also has no mechanism for including multi-bounce effects. NPATCH, on the other hand, employs SBR physics to tackle the near-field illumination/multi-bounce scattering problem for complex 3-D realistic targets.

NPATCH - A prototype near-field scattering predictor: In a successful encounter, the missile passes from the far-field scattering zone, through the intermediate-zone and into the near-zone of the target (see Fig. 1). Most radar scattering predictors, including the widely accepted XPATCH, make the assumption that the target is in the far-field of the radar. The far-field assumption is that the wavefront incident at the target has uniform magnitude and phase, and the scattered wave arrives back at the radar antenna from a single direction, as shown in Figure 1. In the near-zone, however, the missile and target are in close proximity, and an EM wavefront of nonuniform magnitude and phase dictates the complete scattering phenomena. So, far-field assumptions lead to gross errors under near-field conditions. Figure 1 illustrates the important differences between near-field and far-field missile/target encounter situations. This is why a near-field capability such as NPATCH is essential for end-game applications.

NPATCH is designed to model an end-game encounter from the intermediate-zone into the near-zone of an airborne target. The specific modeling process of the NPATCH model is illustrated as in Figure 2. A missile is located at point $\mathbf{R_m}$ and has an instantaneous velocity $\boldsymbol{v}_\mathbf{m}$; its target is located at point $\mathbf{R_t}$ with velocity $\boldsymbol{v}_\mathbf{t}$. The antenna (located at $\mathbf{R_a}$), as mounted on the missile, has a radiation pattern $\mathbf{A}(\theta_m, \phi_m)$. This antenna illuminates the target, which scatters energy in all directions. Some of that energy scatters back toward the missile and is partially absorbed by the antenna. The quantity of interest is the ratio of the received power to the transmitted power P_r/P_t at the antenna terminals, including the phase shift, as a function of frequency. The SBR method is applied to compute this quantity in the following manner.

First, the target is illuminated by thousands of rays weighted by the radiation pattern of a mounted missile antenna. These rays are launched from the missile antenna as if emanating from a point source toward the target (see Fig. 3). Notice that the physical missile is replaced with a point source here since the effect of its body on the scattering problem is already characterized by the radiation pattern of the mounted antenna. A CAD ray-tracer is then used to determine which target surfaces are lit and which surfaces are shadowed. Hence, the cast shadow problem is properly handled in the SBR process.

Second, the illuminating rays are treated as ray tubes, which cast "footprints" on the target body. This is shown for several rays in Figure 4. Using physical optics (PO) principles, the induced surface currents over the domain of each footprint are computed. This is where the material properties of the target are incorporated; the computed surface currents depend on the material attribute of the surface at each ray hit point. These currents will radiate in all directions. Using free-space Green's function, we compute the scattered energy at the point $\mathbf{R_a}$ from each footprint. Only a fraction of this energy will be absorbed by the missile antenna, and this will depend on the direction of arrival. Hence, in computing P_r/P_t, we weight the scattered energy at $\mathbf{R_a}$ by the receiving cross-section of the missile antenna at the arrival angle.

Third, the rays which illuminate target surfaces are specularly reflected from their hit points. The ray tracer continues to trace these rays until they escape. Some will escape after the first bounce, and they produce no further contributions at the receiver. This process produces the 1st-bounce contribution similar to NcPTD. Others will become multi-bounce rays, also shown in Figure 3. These rays continue to induce further currents on the target surface, which are then radiated back to the missile antenna in the same manner as described above. As a result, they also contribute to the radar received power. In this sense, SBR is a multi-bounce implementation of physical optics for complex target interactions. The advantage of this approach is that the target can be very complicated and realistic and SBR can produce much more accurate near-field scattering results than past codes, like NcPTD and other available near-field predictors.

NPATCH uses sophisticated 3D CAD models representing realistic complex targets for its target geometry file. Many target CAD models are typically composed of 10,000 - 200,000 facets (triangular surfaces), or 10,000 to 50,000 bi-cubic patches, depending on the target level of detail. Effective SBR techniques require a fast ray tracer to track the 10,000 - 10 million rays required to fully interrogate complex geometries. NPATCH employs DEMACO's ray tracer, which supports CAD models described in facet (ACAD), bi-cubic (IGES-114) and NURB (IGES-128) formats. This same ray tracer, developed over the past 8 years, is currently used in XPATCH for the Air Force's production aircraft far-field signature synthesis efforts.

Engine modulation: Realistic airborne targets also include jet engines, propellers, or rotors. In a dynamic encounter, these components rotate rapidly, introducing amplitude and phase modulation in the target scattered signal. For aspect angles with 0^o - 70^o of head-on incidence, the engine cavity contribution to the overall radar return of the aircraft can be quite large, and SBR is suitable for predicting this effect. The modulation manifests itself as additional Doppler spectra in the missile radar received. For instance , a 50-blade spool on a turbine rotating at 10,000 rpm has a fundamental frequency of 8,333 Hz. In a pulse-Doppler radar of a missile, this will be manifested as a series of spectra (8.3 KHz, 16.7 KHz, *etc.*) about the "DC" or "skin" line of the moving target. A tracking radar locking onto one of these lines, will generate a highly inaccurate estimate of the target closing velocity.

While this modulation can be predicated with SBR by repeating the simulation for multiple engine blade rotation positions, this is not efficient, since it also repeats the scattering computation on the entire target static components. A better approach, currently being developed in NPATCH, is to separate the engine cavity scattering from that of the rest of the aircraft. In this way, only the scattering computation for the engine(s) must be repeated to obtain the modulated scattered signal from the target. This scheme is illustrated in Figure 5. By employing this method, we are able to recover the same modulated signal as produced by brute-force repetition, but at reduced computational effort. An example is provided in the following section.

3.0 SIMULATION RESULTS

To demonstrate the capabilities and validity of the newly developed NPATCH scattering predictor, we have applied it to a variety of simple and complex 3-D targets in end-game (near-field) encounters with a missile. The approach taken here is to incrementally demonstrate and validate the NPATCH capability and its SBR model. Input to NPATCH specifies the target CAD file and surface material attributes (*e.g.*, metallic surface, dielectric layers), defines a fixed trajectory encounter between the missile and target, describes the missile transmission and receiving patterns, and sets other electromagnetic parameters (*e.g.*, frequency, ray density, maximum number of bounces). NPATCH output is the missile radar received power as a function of time (*i.e.*, missile and target position).

Over the last decade, the NAWCWPNS has conducted experimental measurements for end-game encounter testing involving many different targets and fuzes in our Encounter Simulation Laboratory (ESL) and Missile Engagement Simulation Activity (MESA). These data will be used to validate our near-field modeling simulations. In particular, the encounter test data for simple targets such as cylinder and almond with simple fuze antennas are most appropriate for our near-field scattering predictor' capability check during the current development effort. We will also compare the NPATCH single bounce and multi-bounce predictions on a more complex multi-bounce geometry to show the extra contributions that a multi-bounce implementation can generate.

Case 1: A Cylinder: NPATCH is first applied to a solid, metallic cylinder in a end-game simulation. The arrangement for the end-game encounter is shown in Figure 6 for a missile moving on a linear track under a solid, metal cylinder. The missile fixture has a 14-element array whose main beam points 10° forward of broadside. Experimental measurements for this scenario were conducted in the NAWCWPNS Encounter Simulation Laboratory in early 1990. This measurement was used to validate the single bounce missile/target code, NcPTD. The same measured data are used to validate the NPATCH code. As can be seen in Figure 7, the computed results compared very favorably with the measured data and NcPTD computation. Since NPATCH and NcPTD implement PO on the first bounce, it is to be expected that NPATCH and NcPTD should closely agree in Cases 1 and 2, which involve a simple, convex (*i.e.*, single-bounce) geometry.

Case 2: An Almond: NPATCH is next applied to a new target, an almond, which is a standard target for the DOD/NASA Electromagnetic Code Consortium. This is to demonstrate its capability in handling near-field scattering returns, range gating and material coating. The comparison is shown in Figures 8 to 11. The results agree well with results obtained from NcPTD.

Case 3: A MIG-29 CAD model: This case, illustrated in Figure 12, involves the sort of realistic CAD model geometry that goes beyond the capabilities of codes like NcPTD. The MIG-29 model offers ample opportunities for multi-bounce scattering mechanisms, and this is evidenced in the NPATCH predicted scattering returns shown in Figure 12. For the single-bounce curve, NPATCH is directed to stop ray tracing after the 1st-bounce, so only scattering due to directly illuminated surfaces is observed. For the multi-bounce trace, NPATCH is directed to trace rays up to 50 bounces. Clearly, much of the scattering response for this combination of CAD model and missile path comes from indirectly illuminates surfaces - that is, surfaces illuminated by energy reflected off other parts of the aircraft body. The radar frequency for this prediction is 10 GHz, and the antenna pattern is identical to the one described in Case 1 and plotted in Figure 8. The aircraft surfaces are assumed to be perfectly conducting.

Case 4: A Jet Engine: This case, while artificial in its geometric configuration, provides proof-of-concept for the efficient engine modulation technique described earlier. Figure 13 shows a P3 aircraft CAD model with an extra engine containing a single spool of blades (20). A missile approaches near the engine, illuminating the entire configuration. The main beam of the conical fuze radar antenna point 80° from the missile longitudinal axis. Figure 13 also shows the near-field RCS generated by the NPATCH scattering code as a function of turbine rotation angle. For this near-field configuration, the composite target scattering depends heavily on the turbine blade angle. Because their are 20 uniformly space blades, the periodicity of the rotating spool is 18°. By placing a ray hand-off plane at the engine inlet, and only re-launching hand-off rays for each subsequent blade rotation, a computation time per blade angle is reduced by a factor of three (3) with respect to a straight SBR implementation without ray hand-off and re-launch.

Case 5: Glint from a model F-15 aircraft: In Figure 14, we show a glint result of a model F-15 aircraft. The glint arises from the coherent interaction of multiple scattering points (or centers) on the target body. As the azimuthal incidence angle is swept, relative phase relationships of these centers as observed by the radar changes, producing rapid variations in the combined target scattering signal strength. This phenomena also produces sharp discontinuities in the scattered field phase front incident at the missile and corresponding rapid shifts in the apparent location of the target. The vertical axis of the plot indicates the displacement of the perceived target cross-range location with respect to its actual position.

Case 6: Color Display of Endgame encounter: Finally, Fig. 15 illustrates the graphical display feature of the NPATCH. A full-motion 3-D end-game encounter display was developed in NPATCH to provide visual simulation of the encounter scenario for missile performance assessment and diagnostic analysis. This tool shows the time-stepped end-game encounter in 3-D, with full rendering of the target and missile from their 3-D CAD models. A unique feature is the target surfaces color-coding according to the strength of the target surface scattering contribution back toward the missile. The missile is displayed flying past the target, with overlays of scattering regions sweeping across the target. This capability has important diagnostic value for the user, and will be incorporated into a full 3-D Encounter and Analysis GUI in the coming years.

4.0 CONCLUSION

As a result of our effort to improve radar-target scattering modeling capability for endgame simulation, a prototype near-field scattering predictor, NPATCH, was developed. NPATCH is a deterministic, multi-bounce EM scattering model which simulate the radar signature of an airborne target from mid-course to endgame. Features include non-uniform target illumination by arbitrary missile antenna patterns (and non-uniform scattering reception), mono-static and bi-static modes, multi-bounce scattering, user-configured time gates, and support for realistic 3-D targets with material coatings. More specifically, we have developed a prototype deterministic near-field scattering predictor that has now been demonstrated and incrementally validated.

In the coming years, our development efforts will be primarily focused on studying different ways to augment the EM modeling to include clutter, jamming, Doppler spectra, and engine modulation. These are all EM phenomena and are important to maximize the realism of the simulation. The main goals of future effort are:

1) Augment the EM scattering predictor to incorporate clutter, jamming, and engine modulation.
2) Augment the EM scattering predictor to generate near-field smeared Doppler data suitable for input to a radar simulation module.
3) Add needed features to EM scattering predictor which include
   i) bi-static operation, as with semi-active homing systems where the illuminator is a fixed ground or sea unit, and
   ii) tracking antenna gimbaling.
4) Develop a graphical users interface for the near-field code and develop analyst tools to evaluate the cause and effect of near-field scattering from complex targets represented by IGES and Facet 3-D CAD.

In addition, we will use the experience gained in developing the near-field predictor prototype and the far-field predictions to build a full Target Scatterer model suitable from the near-field out to the far-field. The software coding to build this model is fairly substantial, involving CAD model processors, 3-D ray tracers, antenna pattern look-up tables, ray tube physics, and surface current radiation. In pursuing the development effort, we will leverage off current COTS and GOTS software technologies and products to produce a near-field target scattering code which is, itself, highly modular. Furthermore, we will transition the SBR and related technologies to an object-oriented programming format that will greatly facilitate code re-usability.

5.0 REFERENCES

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[4] D.J. Andersh, S.W. Lee, *et al.*, "XPATCH: a high frequency electromagnetic scattering prediction code and environment for complex three-dimensional objects," *IEEE Antennas and Propagation Magazine*, vol. 36, no. 1, Feb. 1994, pp. 65 - 69.

6.0 FIGURES

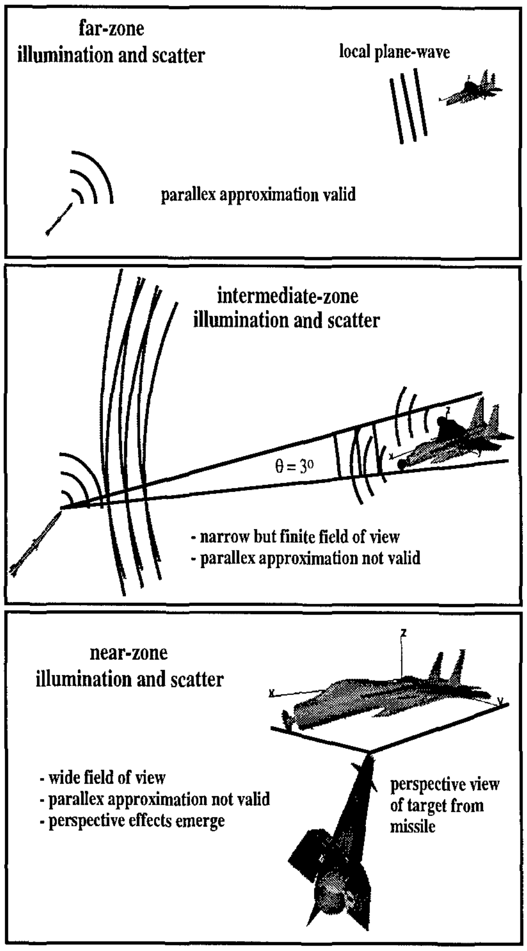

Figure 1. Definition of far-zone, intermediate-zone, and near-zone for a missile encounter with a target.

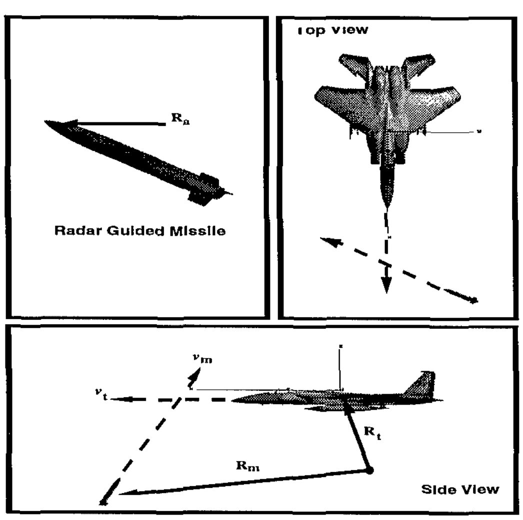

Figure 2. End-game encounter between missile and target.

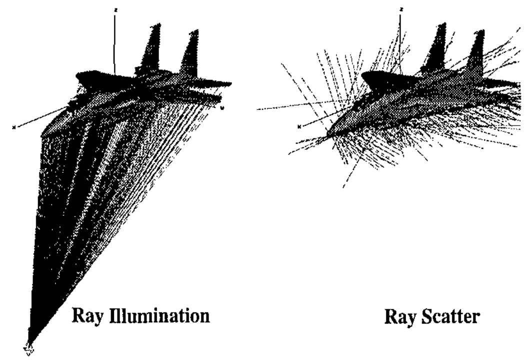

Figure 3. Antenna pattern-weighted rays are launched from missile and scatter off of the target, leaving surface currents that radiate back to the missile.

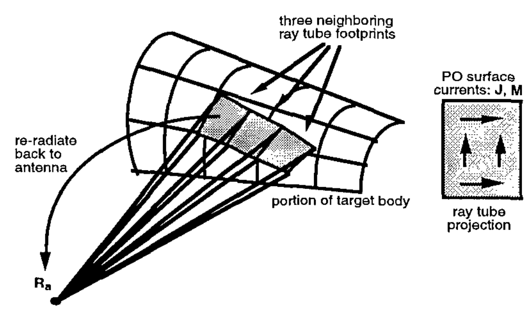

Figure 4. Rays launched from missile antenna project ray tubes on to target surface.

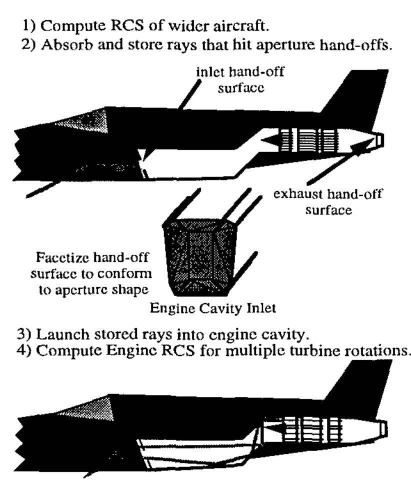

Figure 5. Technique for efficient engine modulation with SBR.

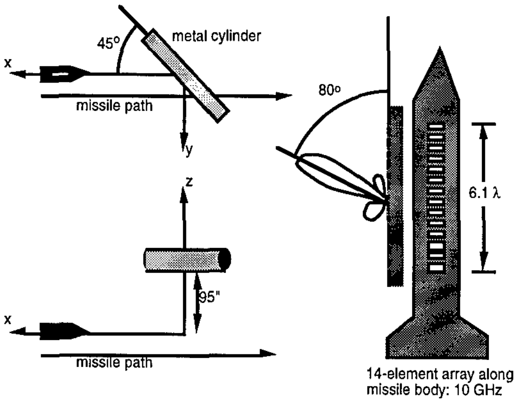

Figure 6. Linear path of missile past cylinder target for NAWC, China Lake measurement.

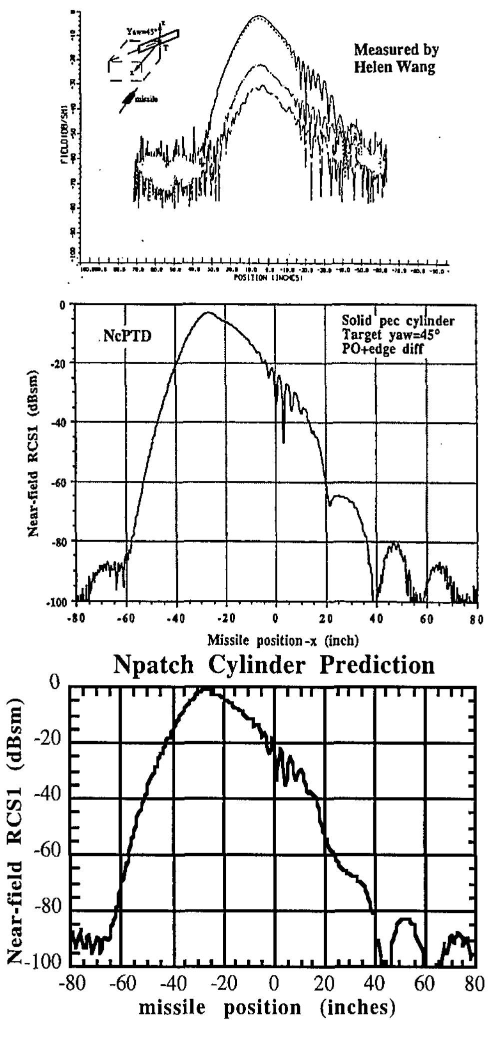

Figure 7. Near-field RCS results of a cylinder versus missile position: measurement, NcPTD prediction, and NPATCH prediction.

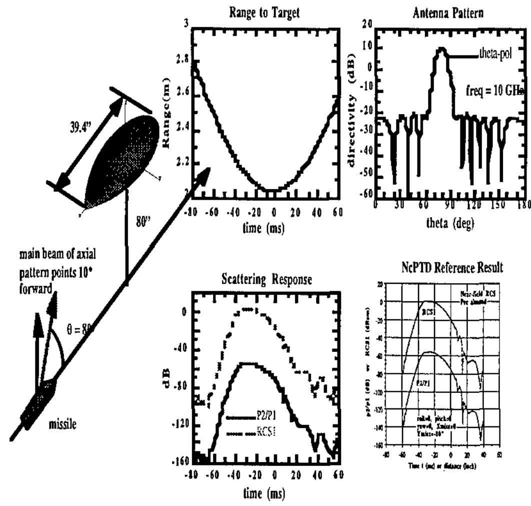

Figure 8. Almond (PEC) results demonstrating near-field scattering response.

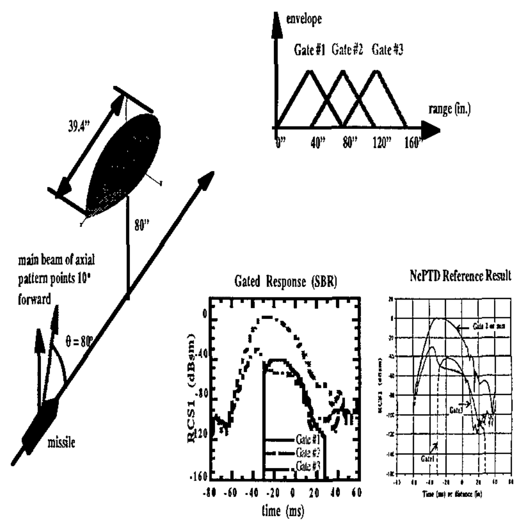

Figure 9. Almond (PEC) results demonstrating range gating effect.

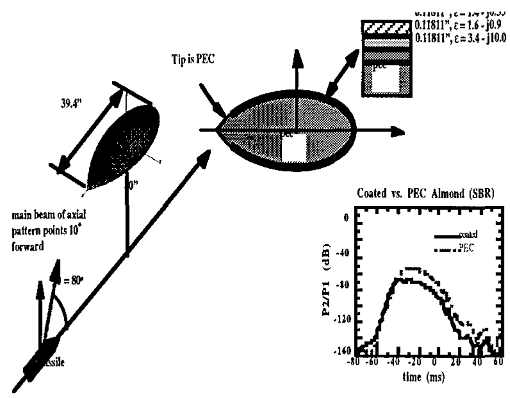

Figure 10. Almond results demonstrating material coating effect.

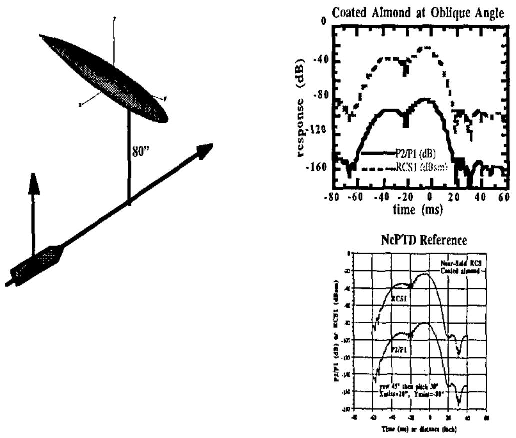

Figure 11. Almond results demonstrating material coating effect.

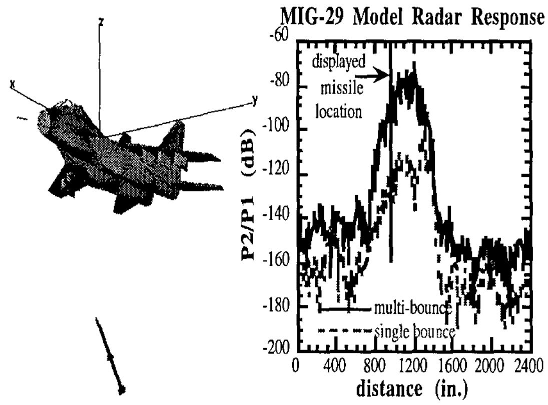

Figure 12. Significance of multi-bounce in MIG-29 model scattering return predicted by NPATCH.

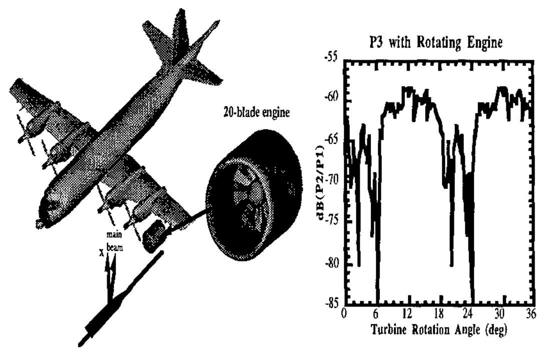

Figure 13. Periodic scattering signal from a model P3 aircraft with rotating engine.

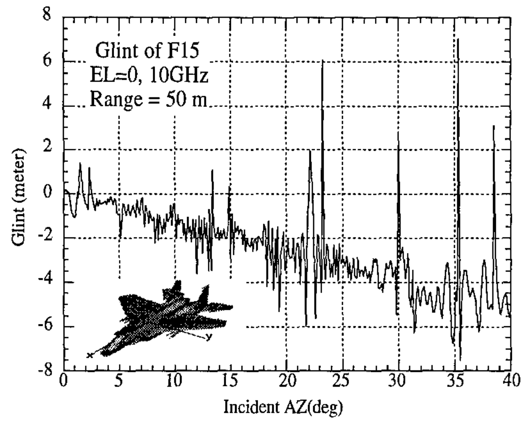

Figure 14. Glint of model aircraft F-15 calculated from NPATCH.

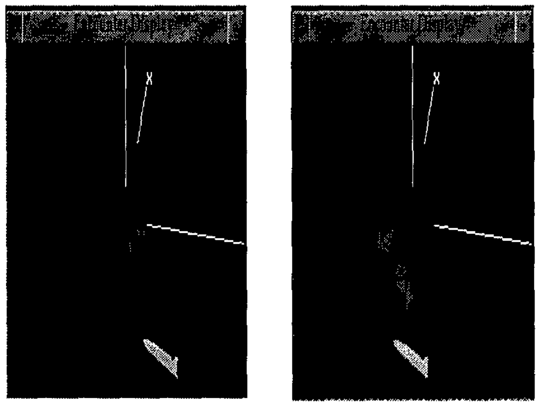

Figure 15. Scattering hot-spots overlay on target for endgame missile fly-by.

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